Modeling of an Automotive ThermoElectric Generator (ATEG)

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Abstract: ***This paper studies an ATEG system which works on the temperature difference between the exhaust gases (hot side) and circulating engine coolant liquid (cold side) of an Internal Combustion (IC) engine. The approach taken in this paper is theoretical analysis by understanding the basic physics (mathematical equations) of the ATEG system. These mathematical equations are modeled in MATLAB/Simulink environment for computer simulation. The inputs to this model, for simulation, are given from the IC engine test bench data. The results indicate that the ATEG system is suitable to drive all the electrical loads in a small (< 1.4 liter engine) and midsized (between 1.4 liter and 2 liter engine) IC engine driven Automobiles. Therefore, ATEG system forms a great candidate to replace the alternator for small and midsized Automobiles. Replacing the alternator by the ATEG eliminates the load of the alternator on the IC engine and increases the overall fuel efficiency of the automobile greatly (about 4-7% depending on the IC engine and electrical demand of the car).***

Keywords: ATEG, MATLAB/Simulink, exhaust gas, engine coolant liquid

1. Introduction

With the ever increasing environmental effects of fossil fuels, it has become the utmost priority of engineers and scientists around the world to improve the efficiency of IC engines. One such way is to recover waste heat from the exhaust gases in an automobile. In a typical IC engine driven automobile, only about 25% of the energy supplied by the fuel is used vehicle mobility and accessories. About 40% of the energy is reflected in the form of heat in exhaust gases and about 30% is reflected in the form of the heat carried away by the engine coolant liquid [1, 2]. This is pictorially represented in figure 1.

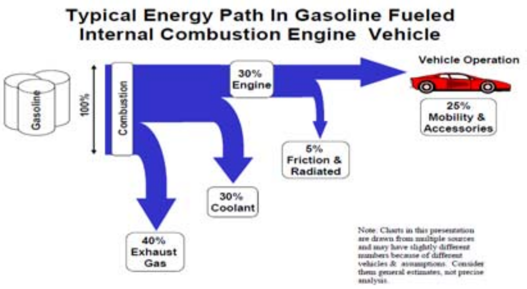

Figure 1: Typical energy flow in an IC engine driven automobiles

One heat recovery technique is the ThermoElectric Generator (TEG), which recovers heat from the IC engine exhaust and converts a part of it to electricity.

TEG has no moving parts and is not bulky and hence is very suitable for automotive applications. With the improvements in the material technology, TEGs power output and efficiency of conversion (thermal to electrical) has improved to a significant level so that the applications of TEGs in an automobile have become viable (technically and financially). This electricity generated by the TEG can substitute/eliminate fossil fuel based electricity generated in the automobile by the alternator (existing automobiles).

When we adapt TEG technology to an automobile, we generally call the system an Automotive ThermoElectric Generator (ATEG). The approach taken in this paper is to model the ATEG system for computer simulation. The initial design is optimized by the modeling approach, and by doing this we significantly save cost involved in testing a physical prototype in the laboratory. The obvious succeeding step to this model based design approach is to validate the design in simulation environment with a physical prototype giving the same inputs to both the model (simulation environment) and physical prototype. The entire modeling and simulation activities were carried out in MATLAB/Simulink environment. The inputs to this model are given from the test bench data of the target IC engine. The detailed ATEG conceptual design, modeling approach, simulation results are explained in detail in the following sections.

2. Thermoelectric or the Seebeck effect

The Seebeck effect is the conversion of temperature differences directly into electricity and is named after the Baltic German physicist Thomas Johann Seebeck, who, in 1821 discovered that a compass needle would be deflected by a closed loop formed by two metals joined in two places, with a temperature difference between the junctions. [9]

ThermoElectric Generators (TEG) are devices which convert heat (temperature differences) directly into electrical energy, using a phenomenon called the "Seebeck effect" (or "thermoelectric effect"). Older TEG devices used bimetallic junctions and were bulky. More recent devices use semiconductor p-n junctions. These are solid state devices and unlike dynamos have no moving parts, with the occasional exception of a fan or pump. [3, 9]

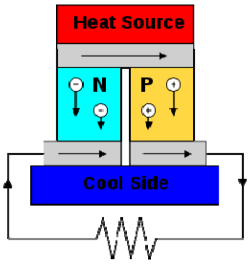

Figure 2 Conversion from heat energy to electrical energy by the TEG

When we realize TEG concept to the automobile, the hot side is the exhaust gases and the cold side is generally the IC engine coolant liquid, though the cold side can be the ambient air or a circulating fluid dedicated to the ATEG system. [4]

3. Basic physics governing the ATEG system

3.1 Figure of merit – ZT

The effectiveness of a thermoelectric material is given by a dimensionless parameter called its' "figure of merit – ZT", given by equation (1).

$$ZT = \frac{\alpha^2\sigma}{\lambda}T \quad (1)$$

Where,
α → Seebeck coefficient of TE material (V/degC)
σ → Thermal Conductivity of TE material (S/m)
λ → Thermal conductivity of TE material (W/mK)
T → Absolute Temperature of TE material (K)

The ZTs of both p-type and n-type semiconductor thermoelectric materials are shown in figure 3.

3.2 Efficiency of conversion

Efficiency of a thermoelectric device is directly related to the overall device ZT (combination of all the individual material's ZT), as shown in equation (2) [5]

$$\eta_{TE} = \frac{T_h - T_c}{T_h}\cdot\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h} \quad (2)$$

Where,
T_h → Hot side Temperature (K)
T_c → Cold side temperature (K)

As ZT of the device increases, the efficiency increases and vice versa. Theoretically ZT of a material can increase to infinity, leading to device efficiency equal to the Carnot efficiency (working between the same temperature limits).

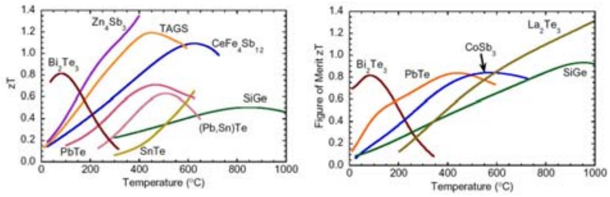

Figure 3: Figure of merit ZT of p-type and n-type semiconductor thermoelectric materials (ZT vs. T of thermoelectric material) [5]

3.3 Heat transfer and electrical parameters

We know that, efficiency is nothing but the input (heat transfer) over the output (electrical power). Therefore, by modeling heat transfer through the thermoelectric materials, we can get the electrical power output.

Heat transfer through the thermoelectric material is treated as a thermal resistance network with exhaust gas, exhaust pipe, ceramic layer, metal contacts (hot side), thermoelectric material, metal contacts (cold side), coolant pipe and coolant liquid treated as series elements. Equation (3) illustrates this equation. [7]

$Q = T_1 - T_2 / R_{th}$ (3)

Where,

Q → heat transfer (W)
R_{th} → Total thermal resistance of all the elements connected in series or parallel (K/W)

T_1 → Hot side temperature (K)
T_2 → Cold side temperature (K)

The electrical power obtained from the ATEG can again be divided into its voltage and current. The Seebeck coefficient (S) of the thermoelectric material is used to estimate the voltage across a material. This is illustrated in equation (4)

$V = S*(T_1 - T_2)$ (4)
Where,
V → Voltage (V)
S → Seebeck coefficient (V/K)

The remaining electrical power is treated as the current through the thermoelectric material.

4. Modeling of ATEG

The above said basic physics is used to model a single thermoelectric material. Many such thermoelectric materials are connected together keeping in mind the cost constraint, space constraint (volume constraint) and the target electrical demand of the automobile [6]. ATEG system is modeled and simulated in MATLAB/Simulink environment. The model requires the exhaust gas and engine coolant liquid's temperature and mass flow rate as inputs and the geometrical dimensions of the thermoelectric material(s) and their properties as model parameters, as shown in figure 4.

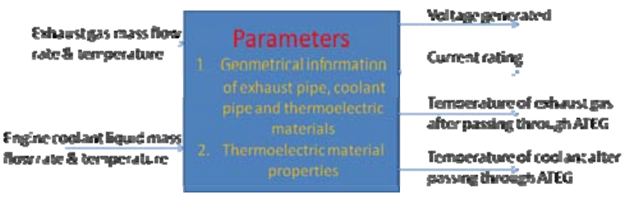

Figure 4: Inputs, outputs and parameters for the ATEG model developed in MATLAB/Simulink

The inputs to this model are given from the target engine test bench data. Another important consideration is the place in the exhaust and coolant pipe, that these inputs are taken. The place of installation of the target ATEG in the automobile is shown in figure 5. A detailed description of the flow characteristics of the various fluids (in an IC engine) is given in [8].

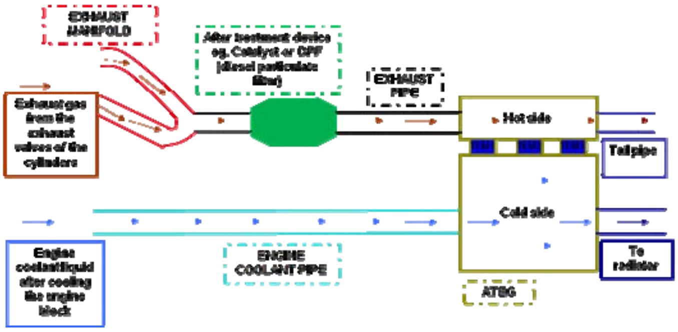

Figure 5: Place of installation of ATEG

5. Simulation Results

For a typical drive cycle profile, the inputs of exhaust gas temperature and mass flow rate are given from a 1.4l diesel engine test bench data for 3600 seconds. A typical drive cycle profile (vehicle speed) is as shown in figure 6.

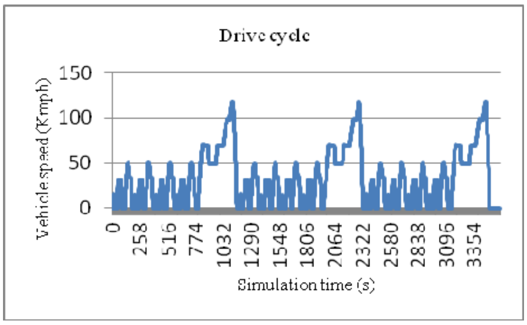

Figure 6: Typical drive cycle profile

The figures 7 & 8 show the inputs, of the exhaust gas, given to the ATEG model from the engine test bench. The engine coolant temperature and mass flow rates are fixed to the value at which the thermostat at the coolant path opens. It's values are 363 K & 0.315 Kg/s repectively.

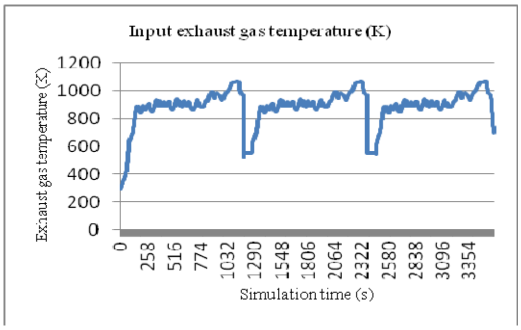

Figure 7: Exhaust gas temperature (K) taken from the engine test bench

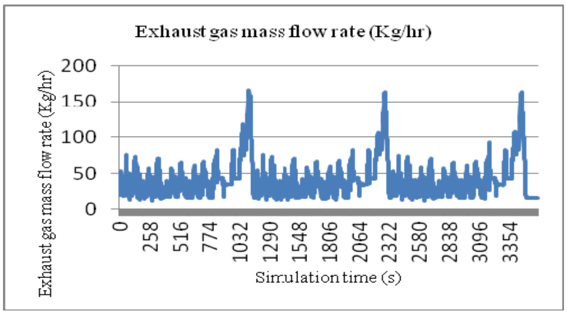

Figure 8: Exhaust gas mass flow rate (Kg/hr) taken from the engine test bench

The results obtained are shown in the following figures 9, 10, 11, 12 and 13.

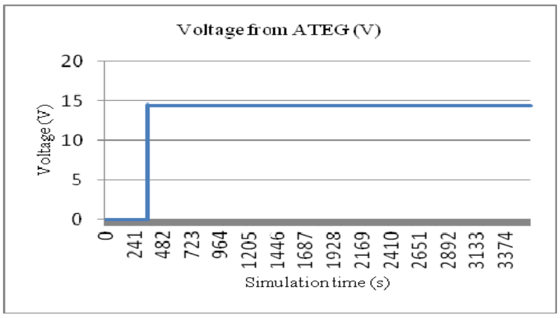

Figure 9: Voltage (V) from ATEG (y axis) vs time (x axis)

As we can see from figure 9, the voltage from the ATEG is kept constant at a value of 14.4V. This is done by the DC-DC converter model and a constant voltage is required to charge the battery. The values from the ATEG for approximately the first 300 seconds are 0. This is due to the time taken by exhaust gas to warm up the exhaust pipe. Figure 10 shows the variation of the current (in Amps) for a drive cycle input. Figure 11 gives the electrical power from the ATEG. This is obtained by multiplying the Current and Voltage from the ATEG. As we can see, the peaks go beyond 1 KW (1000 W) but the average electrical power obtained over a drive cycle is about 600 W. This is similar to the average power obtained by the alternator in an automobile and hence ATEG can be used to replace the alternator and achieve increase in fuel efficiency.

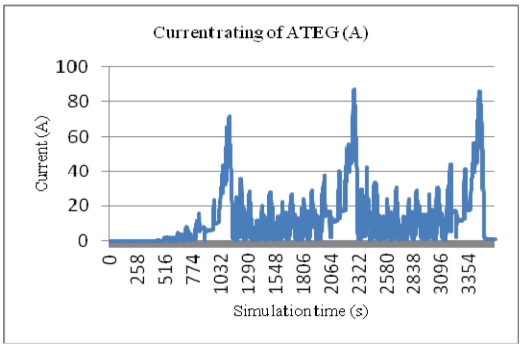

Figure 10: Current rating (A) of ATEG (y axis) vs time (x axis)

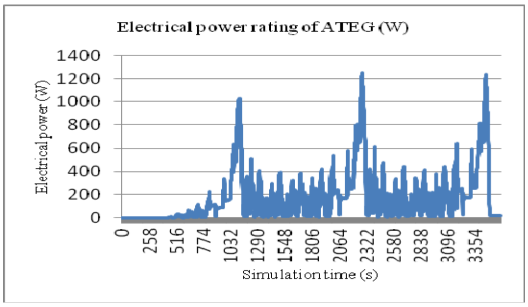

Figure 11: Electrical power rating (W) of ATEG (y axis) vs time (x axis)

Figures 12 & 13 show the Exhaust gas temperature (in K) and the engine coolant temperature (in K) after they pass over the ATEG. It can be observed that, the exhaust gas temperature drops significantly about 250 K from the input but the engine coolant temperature does not raise significantly (<10K) after passing over the ATEG.

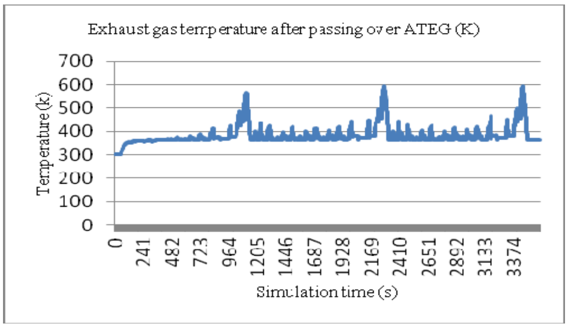

Figure 12: Exhaust gas temperature (K) after passing over ATEG (y axis) vs time (x axis)

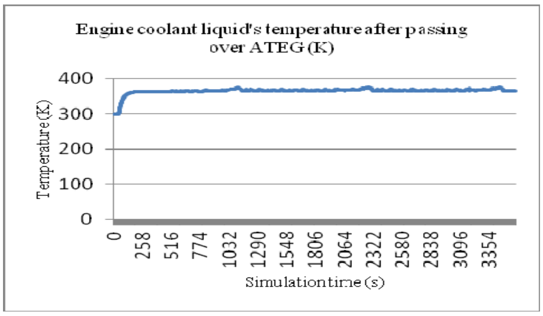

Figure 13: Engine coolant liquid temperature (K) after passing over ATEG (y axis) vs time (x axis)

6. Conclusion

The inputs were given from a 1.4l diesel engine and results show that ATEG can give a comparable power to the alternator in a similar sized IC engine driven automobile. The coolant input temperature is 363 K and we can see from the above results that increasing the radiator size (to increase radiator cooling capacity) is not required.

7. Future Work

The result from the initial model based design is encouraging and the next logical step would be to validate the results from the simulation model with a physical prototype.

This work was carried out at Robert Bosch Engineering & Business Solutions Ltd. (RBEI), Bangalore. The next step of building and validating a physical prototype is being initiated at RBEI. With constant improvement in thermoelectric material technology and the risen interest in energy efficiency has led to a huge business potential for ATEGs.

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Authors' Profile

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